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(54) Edge enhanced error diffusion algorithm.

(57) A method of dynamically adjusting the threshold level (T_n) of an error diffusion algorithm to selectively control the amount of edge enhancement introduced into the encoded output (B_n). The threshold level is selectively modified (40, 42) on a pixel by pixel basis and may be used to increase or decrease the edge enhancement of the output digital image, thus, more closely representing the original detail and edge sharpness of the continuous tone input image (I_n).

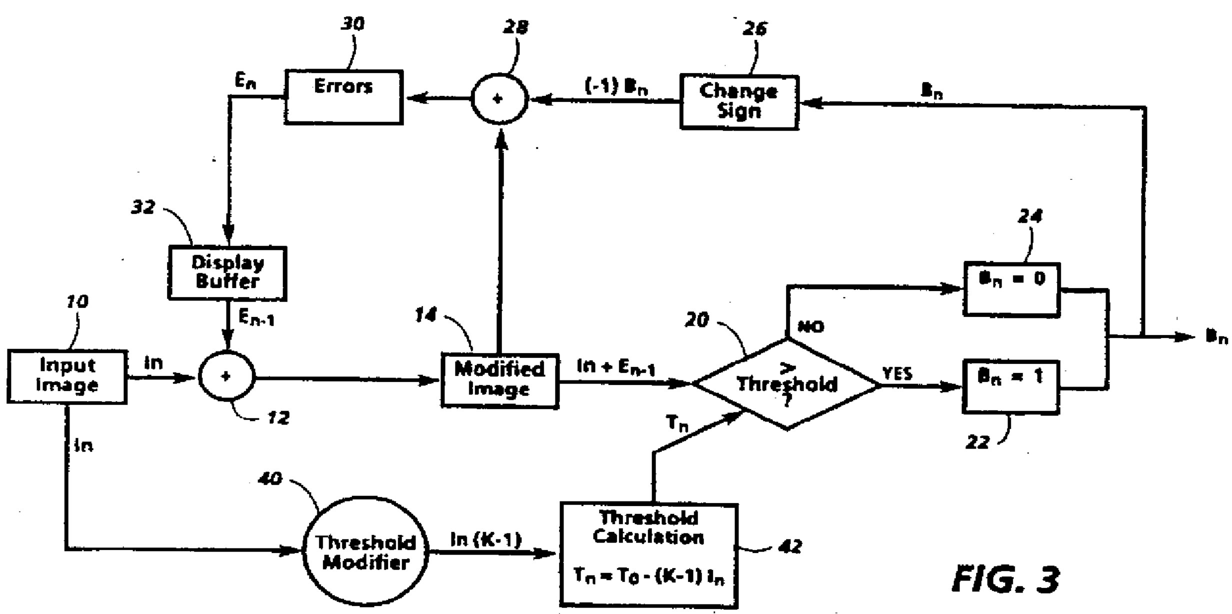


FIG. 3

EDGE ENHANCED ERROR DIFFUSION ALGORITHM

The present invention relates to the representation of digital image data, and in particular, to the binary or multi level representation of images for display purposes.

The representation of continuous tone pictorial data in a binary format is a major concern as the need increases to transmit and display images. The binary representation of image information is desired in order to reduce the sensitivity to noise in transmission and storage or to enable the accurate depiction of continuous tone originals with binary media. In the general field of digital halftoning, there have been disclosed different methods to convert continuous tone to binary images in such a manner as to preserve the appearance of tonal gradation similar to the original image. For example, US-A-4,625,222 to Bassetti et al. discloses a print enhancement control system for an electrostatic copying machine wherein control logic circuitry processes a set of image altering parameters to improve image production quality. These parameters, whose values are either predetermined, fixed or have been received from an exterior source, improve image quality (i.e., resolution) by modifying modulated gray signals.

US-A-4,700,229 to Herrmann et al. discloses an image enhancement circuit which converts a low quality image signal into a high quality image signal by modifying the binary representation of a picture. Image enhancement is accomplished by multiplying a series of error difference signals by a series of weighting factors k(i) which produce a clearer image by improving picture resolution.

US-A-4,672,463 to Tomohisa et al. discloses a method to improve image quality within an electrostatic reproduction machine wherein the sharpness of an image is improved based on the value of an image sharpness control parameter that has been calculated examining the copy quality of an original.

US-A-4,709,250 to Takeuchi discloses an image forming apparatus which improves the halftone image quality of an original. The pulse width of a reference control signal controls and improves image quality in response to a detected image density signal.

US-A-4,724,461 to Rushing discloses an image improving process control for an electrostatic copying machine which maintains high image quality by adjusting a set of process control parameters.

US-A-4,256,401 to Fujimura et al. discloses an image density adjustment method wherein a predetermined image density level within an electrostatic copying machine is maintained at a standard density by varying a set of input control parameters.

US-A-4,693,593 to Gerger discloses a method of improving the image quality by controlling a single process parameter in response to changes in sensitometric characteristics of an image transfer member.

These systems, although providing some degree of image improvement, generally do not provide the means to control the edge enhancement of regions within the image.

Other prior work, such as shown in the Proceedings of the Society for Information Display, Volume 17, 1976, includes a numerical screening algorithm, the Floyd and Steinberg error diffusion algorithm, as a coding technique for the binary encoding of greyscale image data. Modifications to the Floyd - Steinberg algorithm may, as shown by Billotet-Hoffman and Bryngdahl in the Proceedings of the Society for Information Display, Volume 24, 1983, include a varying threshold, a dither, instead of a fixed threshold. This visually decodable technique is presently utilized, for example, in computer displays where the resolution of the output device is limited. The adaptive nature of the Floyd - Steinberg algorithm automatically provides a sharp, edge-enhanced appearance which, while visually appealing, may not necessarily be desirable in the output image.

A difficulty with the Floyd-Steinberg error diffusion algorithm is that an inherent edge enhancement is built into the algorithm. Analysis of the output of the Floyd - Steinberg error diffusion algorithm illustrates a characteristic overshoot (too dark or too light) at upward and downward transitions, or steps, in the continuous tone digital image data. As used within this specification, continuous tone refers to input data that has been quantized to a larger number of discrete values than intended for the output data.

It is an object of the present invention, therefore, to be able to adjust the edges of a given digital image in a manner to improve the overall appearance of the image. It is another object of the present invention to selectively increase or decrease the amount of edge enhancement in a given digital image using a modified error diffusion algorithm for the encoding of the continuous tone input data.

According to one aspect of the present invention, there is provided a method of image encoding in a system for manipulating and displaying digital images represented by a plurality of pixels, each pixel having a given value, the system having a memory for digitally storing the image pixels and a screen for displaying the image as a raster of pixels having a plurality of output states, the method including the steps of:
comparing the given value of a first pixel with a threshold,
determining the output state of said first pixel depending upon the relationship of the pixel to the output

state,
introducing the variance of the first pixel value from the output state into the deviation of a second pixel value from the threshold to determine the output state of the second pixel,
repeating the steps for each pixel of the digital image, and
selectively changing the threshold level during the image encoding, including analyzing the value of each pixel in order to determine if the threshold level should be changed.

According to another aspect of the invention, there is provided a method of edge enhancement of a digital image in a system for manipulating digital images, represented by a plurality of pixels having greyscale levels, to provide a first and a second pixel state, the method including the steps of:
comparing the greyscale level of a first pixel to a threshold level T_0 to determine a first or second state for said first pixel,
analyzing the greyscale level of a second pixel,
responding to the analysis of the greyscale level of the second pixel to change the threshold level to T_1, and
comparing the greyscale level of the second pixel to the threshold level T_1 to determine a first or second state for said second pixel.

Thus, the present invention enables the dynamic adjustment of the threshold of an error diffusion algorithm to selectively control the amount of edge enhancement introduced into the binary encoded output. The threshold level is selectively modified on a pixel by pixel basis and may be used to increase or decrease the edge enhancement of the output digital image, thus, more closely representing the original detail and edge sharpness of the continuous tone input image, or to improve the perceived quality of the image which might be achieved by intentionally deviating from a faithful representation.

Methods in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings wherein the same reference numerals have been applied to like parts and wherein:

FIG. 1 is a prior art block diagram illustrating the 1-dimensional error diffusion technique;

FIG. 2 is an illustration of the input and corresponding signal output for the prior art technique;

FIG. 3 is a general flow chart of the edge enhancement system in accordance with the present invention; and

FIG. 4 is an illustration of the input and corresponding signal output of the system in Figure 3 in accordance with the present invention.

With respect to FIG. 1, there is shown a generalized block diagram illustrating the prior art Floyd - Steinberg error diffusion algorithm for displaying continuous tone digital images. The algorithm has been simplified to a 1-dimensional representation for clarity, however, it should be recognized that the algorithm is extensible to multidimensional systems. The algorithm may be expressed as,

$$B(n) = \mathrm{step}[\, I(n) + \sum_{i=0}^{n-1} \{ I(i) - B(i) \} \quad T_0], \tag{1}$$

where the output signal B(n) is a function of the input signal I(n) and a threshold T_0

The error diffusion algorithm is implemented using the constant threshold level T_0 to encode the continuous tone input image. The thresholding, or clipping, of the input pixel results in an output pixel level and an associated error value. The error value is allocated to subsequent pixels based upon an appropriate weighting scheme. Various weighting techniques may be used, for distribution of the error value, to modify the output image generated using the error diffusion algorithm.

With respect to FIG. 1, the image input block 10 introduces the input digital image I_n, into the system on a pixel by pixel basis, where n represents the input image pixel number. Each input pixel has its corresponding error value E_{n-1} added to the input value I_n, at adder block 12, resulting in the modified image block 14, where E_{n-1} is the error value of the previous pixel (n-1). The modified image data, the sum of the input value and the error value of the previous pixel (I_n, + E_{n-1}), is passed to the threshold comparator 20. The modified image data is compared to the constant threshold value T_0, from block 16, to determine the appropriate output level B_n 22 or 24. Once the output level B_n, is determined, it is subtracted from the modified image value to generate the error level E_n for the subsequent input pixel. The subtraction operation is represented by the sign inversion block 26 and subsequent adder block 28, with E_n representing the difference between the modified image value (I_n + E_{n-1}) and the output value B_n for pixel

n, as represented by error block 30. The delay buffer block 32 represents a single pixel delay to store E_n in the simplified 1-dimensional situation. However, a multidimensional implementation would require a larger delay block 32 capable of summing and storing multiple weighted error values.

The cyclical processing of pixels is continued until the end of the continuous tone input data is reached. FIG. 2 illustrates the processing stages of a portion of a typical scanline, with n representing the input image pixel number. In FIG. 2a, In denotes the value of the continuous tone digital input pixels. The modified image value, including the input and error, is represented by $(I_n + E_{n-2,})$ with a constant threshold T_0 superimposed as a dashed line in FIG. 2b. At any point in FIG. 2b that the modified image value $(I_n + E_{n-1})$ exceeds the threshold level T_0, a binary pulse will be output as indicated by curve B_n in FIG. 2c. Specifically, in FIG. 2b, $(I_n + E_{n-1})$ level 80 is below the T_0 threshold level 88, resulting in B_n output level 90 in FIG. 2c and an error E_n equal to the difference between $(I_n + E_{n-1})$ and B_n. Processing of the subsequent input image pixel (n + 1) provides a modified image value 81 in FIG. 2b which is above the T_0 threshold level 88. This results in an output level B_{n+1} indicated by 92 in FIG 2c. The error value to be associated with the following pixel will again be determined by the difference between $(I_{n+1} + E_{(n-1)+1})$ and B_{n+1}, where B_{n+1} is now unity. The modified image value for input pixel (n+2) is indicated by level 82 in FIG. 2b. Continued processing of the input pixels in FIG. 2a would eventually result in a $(I_n + E_{n-1})$ modified image value 83 exceeding the T_0 threshold level 88 and a resultant B_n output level 96. Here, B_n is set to 1 immediately before an I_n input edge transition 72 to 74, resulting in $(I_n + E_{n-1})$ modified image value 84 below T_0 threshold 88 and an output level B_n = 0 at 98. The upward transition, 72 to 74, in input level I_n is thus encoded as a downward transition, 96 to 98 in the B_n output level.

In an embodiment of the system according to the present invention, identification of I(n) and T_0 as independent components of the algorithm allows the representation of the algorithm for encoding of a continuous tone digital image by the expression.

$$B(n) = \mathrm{step}\left[\sum_{i=0}^{n-1} [I(i) - B(i)] - T\{I(n),n\} \right] \qquad (2)$$

where B(n) represents the output of the modified error diffusion algorithm. The threshold term T is shown as a function of both I(n) and n, where n represents the respective pixel position in the input image scanline. This illustrates an additional degree of freedom that can be used to adapt the local pulse distribution to the digital image output requirements, such as controlling edge enhancement. Specific methods for the calculation of threshold T are indicated by the expressions.

$$T\{I(n),n\} = T_0 + (K/(2N+1))\{\sum_{i=n-N}^{n+N} a_i I(i)\} \qquad (3a)$$

$$T\{I(n),n\} = T_0 - (K-1)\,I(n) \qquad (3b)$$

where T_0 is a constant such that $0 \leq T_0 \leq 1$, a_i is a weighting factor and N is an arbitrary nonnegative integer. The enhancement factor K may be held constant or may vary as a function of the input image content, local or global, within the continuous tone input image. Choices for T{I(n),n} include, but are not limited to expressions 3a and 3b above.

With reference to FIG. 3, there is shown a general flow chart of an embodiment of the system according to the present invention, using the expressions 2 and 3b above. The image input block 10 introduces the input digital image I_n into the system on a pixel by pixel basis. Each input pixel has its corresponding error E_{n-1} added to the input value at adder 12, prior to passing the sum to the modified image block 14. The modified image data, the sum of the input value and the error value of the previous input pixel $(I_n + E_{n-1})$, is passed to the threshold comparator block 20.

The modified threshold level T_n is determined by first calculating a modifier based on the input value I_n of each pixel, as represented in the threshold modifier block 40. The modifier value $I_n(K-1)$ is then subtracted from the nominal threshold value T_0 in the threshold calculation block 42, to determine the

threshold value T_n to be applied at the threshold comparator block 20. Alternatively, it is possible to accomplish an equivalent alteration of the threshold through the addition of the modifier value $I_n(K-1)$ to the modified image value ($I_n + E_{n-1}$) while maintaining the threshold value at its nominal level T_0.

The modified image value ($I_n + E_{n-1}$) is compared to the modified threshold level T_n to determine the appropriate output level B_n via blocks 22 and 24. Output level B_n is then subtracted from the modified image value ($I_n + E_{n-1}$) to determine the error level E_n for the subsequent input pixel. The subtraction operation is represented by the sign inversion block 26 and subsequent add block 28, with E_n, at error block 30, representing the difference between the modified image value ($I_n + E_{n-1}$) and the output value B_n. The delay buffer block 32 represents a single pixel delay to store E_n in the simplified 1-dimensional situation.

An illustration of the data associated with the processing of a scanline is shown in FIG. 4. The input value I_n is shown in FIG. 4a, with two typical transition steps 100 and 102. The corresponding modified image values ($I_n + E_{n-1}$) are illustrated in FIG. 4b for the progression of successive pixels, with the modified threshold level T_n superimposed as a dashed line. The transition points 110 and 112 for the threshold T_n correspond with transitions 100 and 102 of I_n due to the fact that the threshold level T_n is now a function of I_n from expression 3b above. At any point that the modified image value ($I_n + E_{n-1}$) exceeds the threshold level T_n, a binary pulse will be output as indicated by curve B_n in FIG. 4c. Specifically, in FIG. 4b the modified image value ($I_n + E_{n-1}$) at 114 is below the threshold level T_n 116, resulting in an output level B_n at 130 as illustrated in FIG. 4c.

Processing of the subsequent input image pixel (n+1) provides a modified image value 118, as shown in FIG. 4b. The modified image value ($I_{n+1} + E_{(n-1+1)}$) 118 is compared to the threshold T_{n+1}, now at level 120 due to the change in the input pixel level I_{n+1} at transition 100. The modified image value ($I_{n+1} + E_{(n-1)+1}$) exceeds the threshold level T_{n+1} resulting in an output level B_{n+1} at 132. Subsequent pixels, for example pixel (n+2) whose modified image value is indicated by 122, will be processed with the lower threshold level T_{n+2} indicated by 120, until another image input transition 102 occurs causing the threshold transition 112. Through the modification of the threshold level T_n at input image transition points 100, 102, there is provided specific control of the amount of edge enhancement produced in this modified error diffusion technique.

While the embodiment described herein is limited to a 1-dimensional representation for the sake of simplified explanation, it should be understood that this technique is designed and intended for use in a multidimensional situation, where the display implementation represents a 2-dimensional situation and the display of time varying data represents a 3-dimensional situation. In addition, use of multiple threshold values T will allow generation of output for any multilevel output display, not being limited to the binary output as described. Furthermore, the threshold level T, while illustrated as a function of a single input pixel, can be implemented as a function of a plurality of input pixels representing a region or neighborhood within the continuous tone input image.

The embodiment described herein can also be expanded to include composite images, such as color images, where each color component might be treated individually by the algorithm, or where a vector quantization technique may be used to treat the image in a composite manner. In the case of color input images, edge enhancement could be used to control the color difference at a color transition while minimizing any effects on the brightness at that location. Further expansion of this embodiment, in the area of computer generated holograms, would enable control of the edge enhancement of an input image to modify the amount of light diffracted into the desired order.

While there has been illustrated and described what is at present considered to be a preferred embodiment of the present invention, it will be appreciated that numerous changes and modifications are likely to occur to those skilled in the art, and it is intended in the appended claims to cover all those changes and modifications which fall within the scope of the present invention.

Claims

1. A method of image encoding in a system for manipulating and displaying digital images represented by a plurality of pixels, each pixel having a given value, the system having a memory for digitally storing the image pixels and a screen for displaying the image as a raster of pixels having a plurality of output states, the method including the steps of:
comparing (20) the given value of a first pixel (I_n) with a threshold (T_n),
determining (22, 24) the output state (B_n) of said first pixel depending upon the relationship of the pixel to the output state,

introducing (12, 14) the variance (E_n) of the first pixel value from the output state into the deviation of a second pixel value from the threshold to determine the output state of the second pixel,
repeating the steps for each pixel of the digital image, and
selectively changing (40, 42) the threshold level (T_n) during the image encoding, including analyzing the value of each pixel in order to determine if the threshold level should be changed.

2. A method of image encoding in a system for displaying digital images represented by a plurality of pixels, each pixel having a given value, the system having a memory for digitally storing the image pixels and a screen for displaying the image as a raster of pixels having a first and a second encoded state, the method including comparing the values of each pixel in sequence with a threshold to determine the encoded states of said pixels, and also including the steps of:
determining the variance of the values of each pixel from the encoded state of said pixels,
introducing the variance of each pixel value from the encoded state into the variance of each successive pixel value, and
comparing the variance of the value of each pixel, including the variance of its previous pixel, to the threshold level to determine the encoded state of the pixel, and
selectively changing the threshold during the image encoding, the step of selectively changing the threshold level including the step of analyzing the values of pixels within a neighborhood of pixels to determine if the threshold should be changed.

3. The method of claim 1 or claim 2 wherein the given values of the pixels are greyscale levels.

4. The method of claim 1 or claim 2 wherein the given values of the pixels are color values.

5. The method of claim 1 or claim 2 wherein the output states or encoded states are determined by comparison to a plurality of thresholds generating a plurality of output states.

6. The method of claim 1 or claim 2 wherein the step of introducing the variance includes the step of adding the variance of each pixel from the output state or the encoded state to the variance of each previous pixel from the output state or the encoded state of said previous pixel.

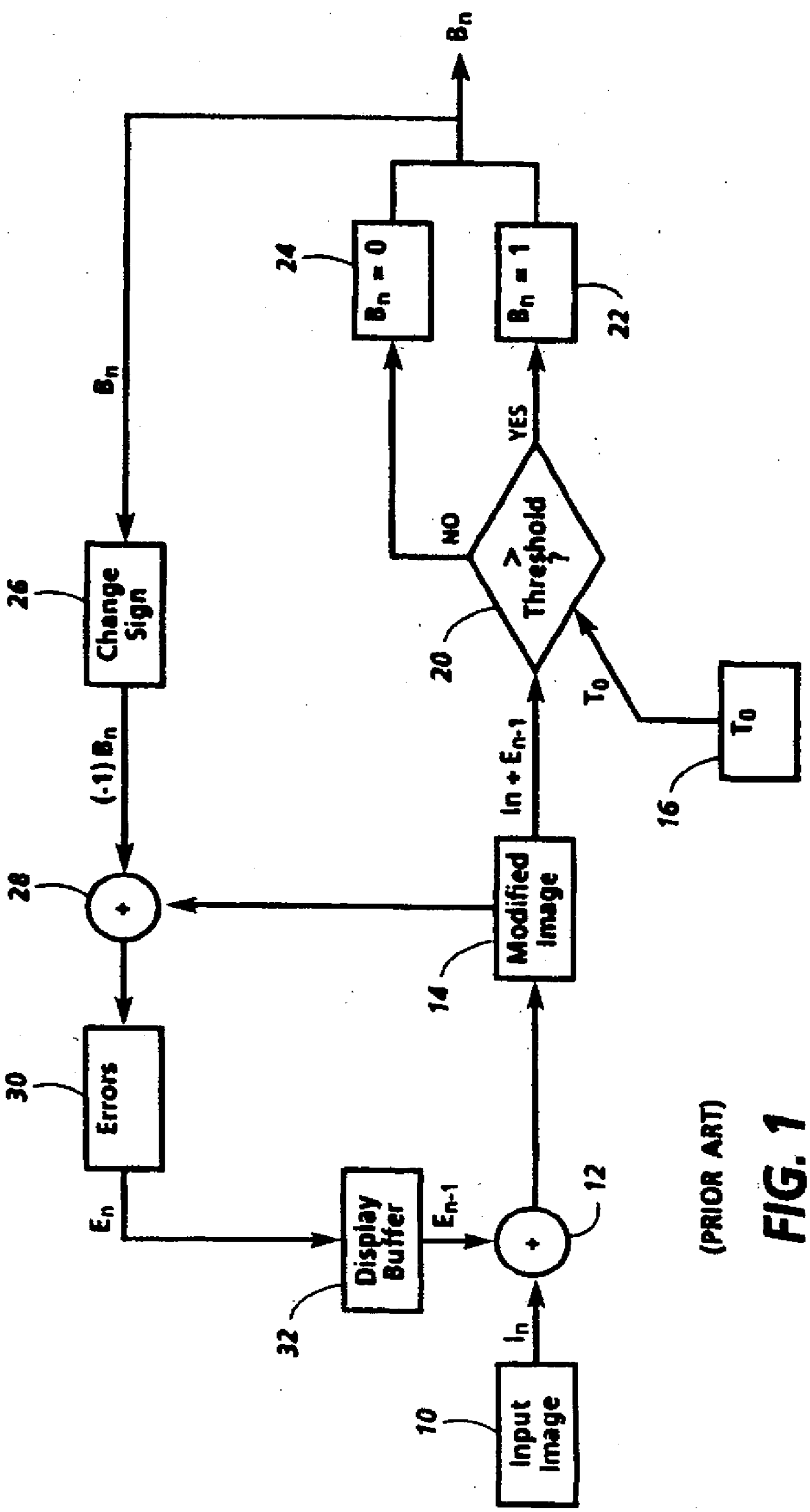
7. A method of edge enhancement of a digital image in a system for manipulating digital images, represented by a plurality of pixels having greyscale levels, to provide a first and a second pixel state, the method including the steps of:
comparing the greyscale level of a first pixel to a threshold level T_0 to determine a first or second state for said first pixel,
analyzing the greyscale level of a second pixel,
responding to the analysis of the greyscale level of the second pixel to change the threshold level to T_1, and
comparing the greyscale level of the second pixel to the threshold level T_1 to determine a first or second state for said second pixel.

8. A method of image edge enhancement in a system for manipulating and displaying digital greyscale images represented by a plurality of pixels, the system having a memory for digitally storing the greyscale image pixels and a screen for displaying the image as a raster of pixels having either a 0 or a 1 output state, the method including the steps of:
determining the 0 or 1 state of a first pixel depending upon the relationship of the pixel greyscale level to the threshold level,
comparing the greyscale level of said first pixel with reference to the 0 or 1 output state to determine the variance of the greyscale level from the output state, and
introducing the variance of the first pixel greyscale level from the output state into the deviation of a second pixel greyscale level from the threshold level to determine the 0 or 1 state of the second greyscale pixel, wherein the improvement comprises the step of analyzing the greyscale level of each pixel in order to determine if the threshold level should be changed.

9. A technique for manipulating a digital image represented by a plurality of pixels, each of the pixels having an associated greyscale level, to provide edge enhancement of the image to be displayed as a raster of said pixels, each pixel of the raster represented by a 0 or 1 output state, including the steps of:
comparing the greyscale level of a first pixel with a reference greyscale threshold level,
determining the 0 or 1 output state of said first pixel depending upon the relationship of the pixel greyscale level to the threshold level,
calculating the variance of the first pixel greyscale level from the output state,
comparing the greyscale level of a second pixel with the reference greyscale threshold level,
determining the 0 or 1 state of said second pixel depending upon the relationship of the pixel greyscale level of the second pixel to the threshold level and depending upon the variance of the first pixel greyscale level from the output state, and selectively adjusting the threshold level for selected pixels in response to

the greyscale level of said selected pixels.

10. A technique for manipulating a digital image represented by a plurality of pixels, each of the pixels having an associated greyscale level, to provide edge enhancement of the image to be displayed as a raster of said pixels, each pixel of the raster being represented by a 0 or 1 encoded state, including the steps of:
comparing the greyscale level of a first pixel with a reference greyscale threshold level,
determining the 0 or 1 encoded state of said first pixel depending upon the relationship of the pixel greyscale level to the threshold level,
calculating the variance of the first pixel greyscale level from the encoded state,
comparing the greyscale level of a second pixel with the reference greyscale threshold level,
determining the 0 or 1 encoded state of said second pixel depending upon the relationship of the pixel greyscale level of the second pixel to the threshold level and depending upon the variance of the first pixel greyscale level from the encode state, and
selectively adjusting the threshold level for selected pixels in response to the greyscale level of said selected pixels.



(PRIOR ART)

FIG. 1

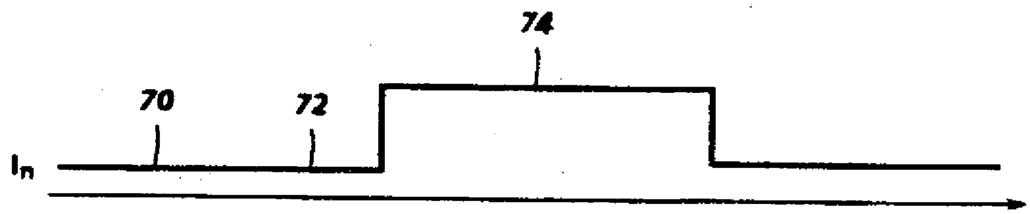


FIG. 2A

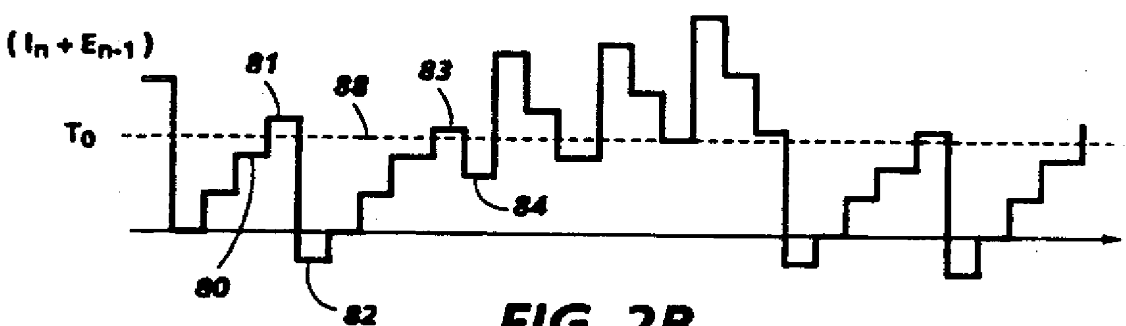


FIG. 2B

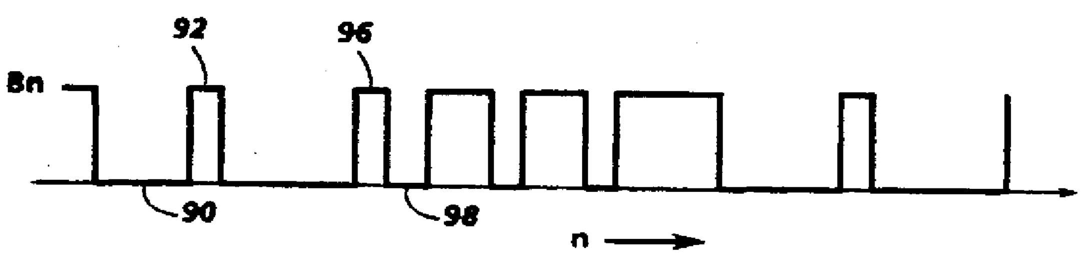


FIG. 2C

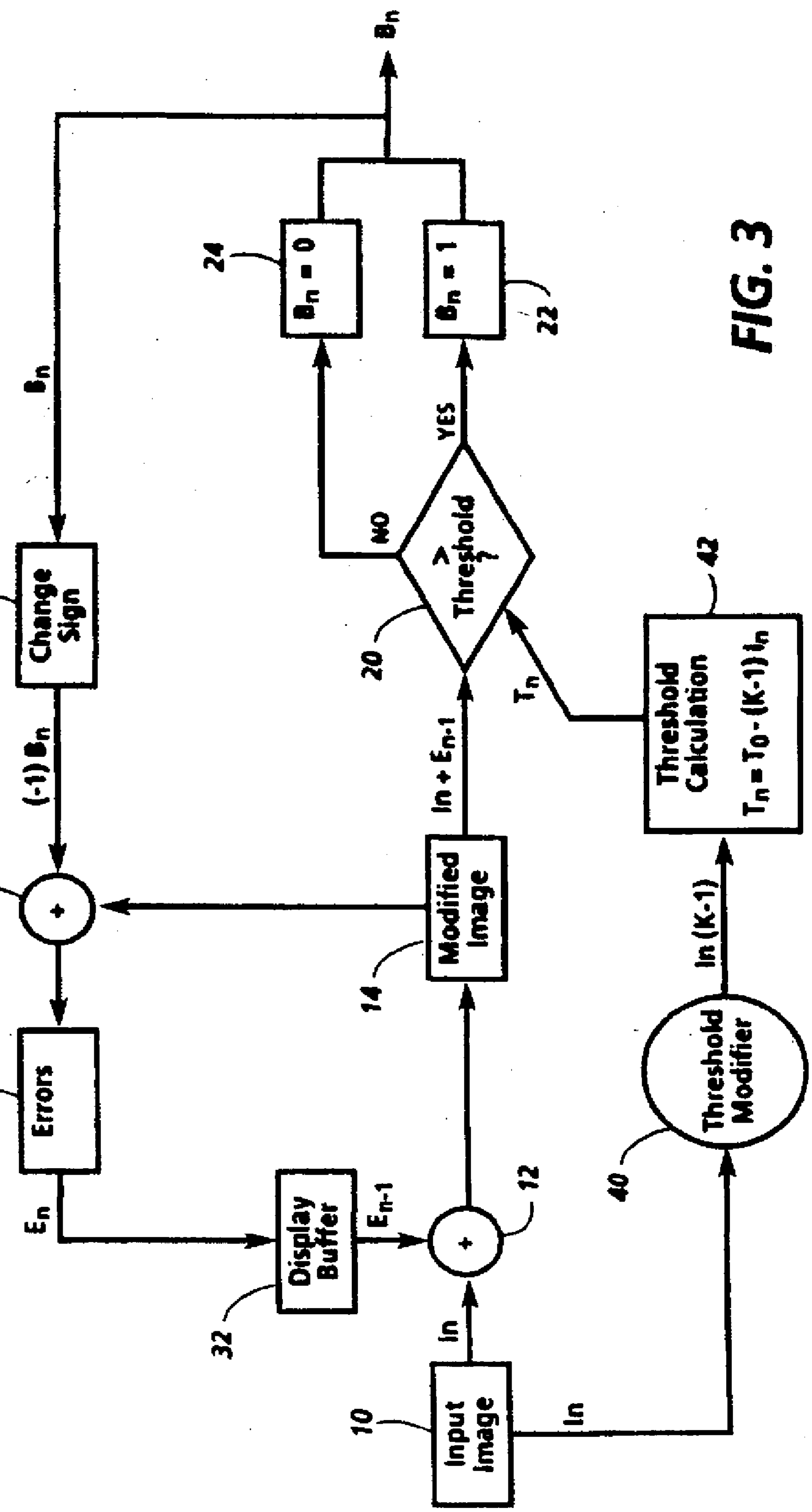

Input Image
Display Buffer
Errors
Change Sign
Modified Image
Threshold ?
$B_n = 0$
$B_n = 1$
Threshold Modifier
Threshold Calculation
$T_n = T_0 - (K-1) I_n$
B_n
$(-1) B_n$
E_n
E_{n-1}
In
In + E_{n-1}
In (K-1)
T_n
NO
YES
10
12
14
20
22
24
26
28
30
32
40
42

FIG. 3

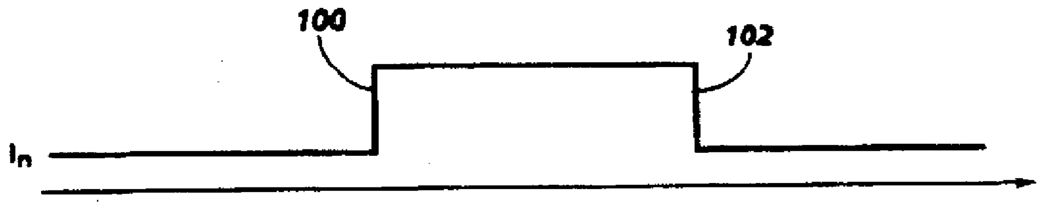


FIG. 4A

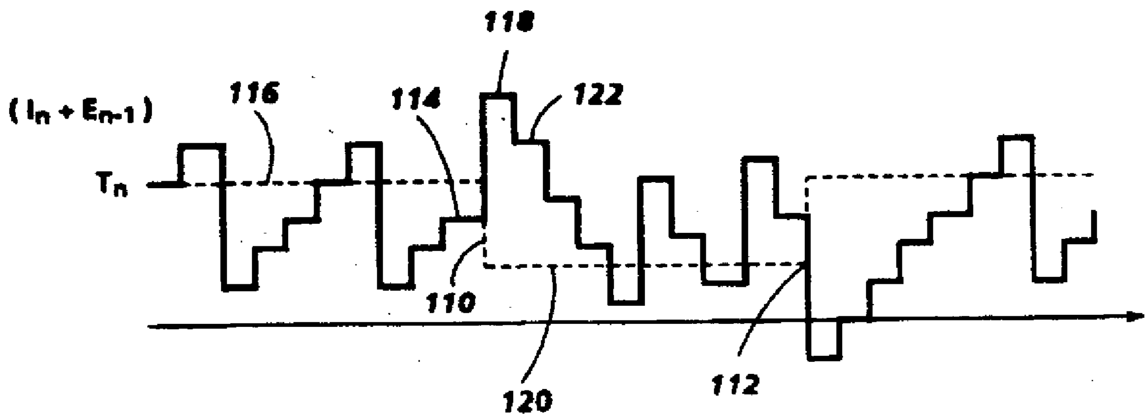


FIG. 4B

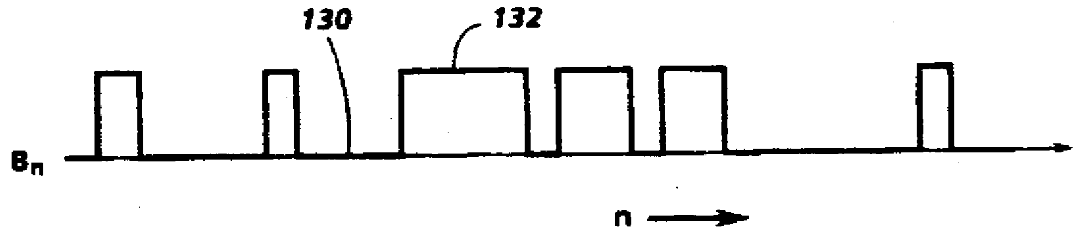


FIG. 4C

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(54) **Edge enhanced error diffusion algorithm.**

(57) A method of dynamically adjusting the threshold level (T_n) of an error diffusion algorithm to selectively control the amount of edge enhancement introduced into the encoded output (B_n). The threshold level is selectively modified (40, 42) on a pixel by pixel basis and may be used to increase or decrease the edge enhancement of the output digital image, thus, more closely representing the original detail and edge sharpness of the continuous tone input image (I_n).

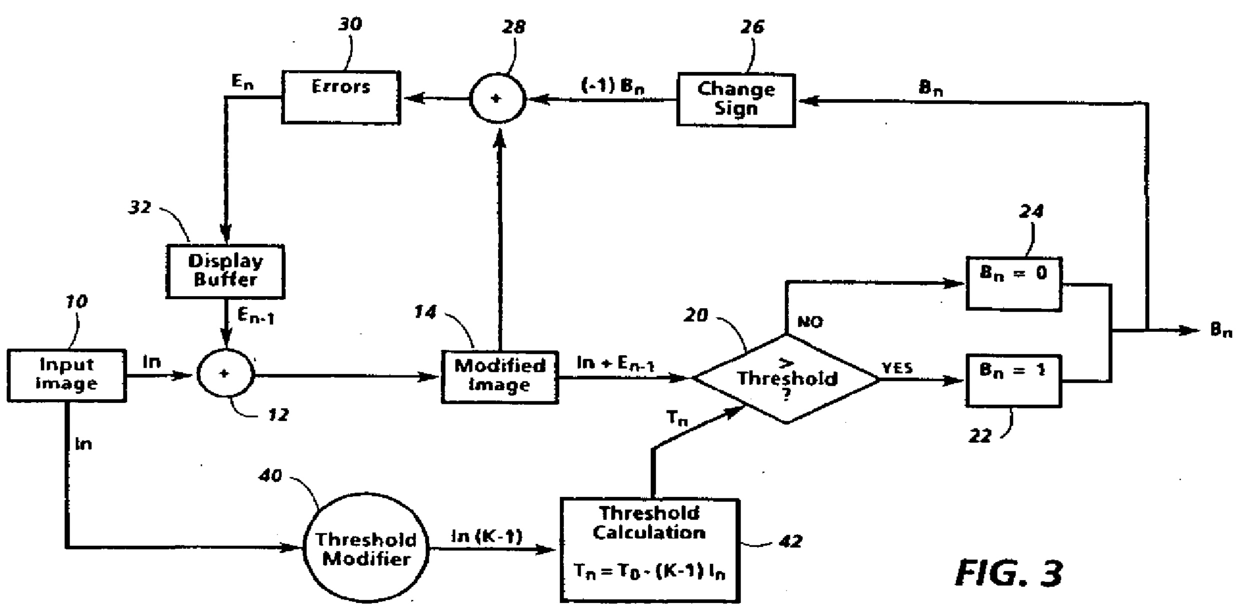

FIG. 3

EP 0 414 505 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 90 30 9172

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	US-A-4 501 016 (PERSOON ET AL) * abstract; claims 1,9; figure 5A * ---	1,2,7,8, 9,10	G06F15/68 H04N1/40 G06K9/38
A	IEEE TRANSACTIONS ON COMMUNICATIONS. vol. 29, no. 12, December 1981, NEW YORK US pages 1898 - 1925; J.C. STOFFEL ET AL: 'A Survey of Electronic Techniques for Pictorial Image Reproduction' * page 1902, left column, paragraph 4 - page 1903, left column * ---	1,2,7,8, 9,10	
D,A	PROCEEDINGS OF THE SID. vol. 24, no. 3, 1983, LOS ANGELES US pages 253 - 258; C. BILLOTET-HOFFMANN ET AL: 'On the Error Diffusion Technique for Electronic Halftoning' * page 257, left column, paragraph 4 * ---	1,2,7,8, 9,10	
D,A	PROCEEDINGS OF THE SID. vol. 17, no. 2, 1976, LOS ANGELES US pages 75 - 77; R.W.FLOYD ET AL: 'An Adaptive Algorithm for Spatial Greyscale' * the whole document * -----	1,2,7,8, 9,10	TECHNICAL FIELDS SEARCHED (Int. Cl.5) H04N G06K G06F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	13 AUGUST 1992	NICHOLLS J.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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